The Connection between Spheroidal Galaxies and QSOs

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Abstract. In view of the extensive evidence of tight inter-relationships between spheroidal galaxies (and galactic bulges) with massive black holes hosted at their centers, a consistent model must deal jointly with the evolution of the two components. We describe one such model, which successfully accounts for the local luminosity function of spheroidal galaxies, for their photometric and chemical properties, for deep galaxy counts in different wavebands, including those in the (sub)-mm region which proved to be critical for current semi-analytic models stemming from the standard hierarchical clustering picture, for clustering properties of SCUBA galaxies, of EROs, and of LBGs, as well as for the local mass function of massive black holes and for quasar evolution. Predictions that can be tested by surveys carried out by SIRTF are presented.

Abbreviations: KAP – Kluwer Academic Publishers; compuscript – Electronically submitted article

JEL codes: D24, L60, 047

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1. Introduction

The hierarchical clustering model with a scale invariant spectrum of density perturbations in a Cold Dark Matter (CDM) dominated universe has proven to be remarkably successful in matching the observed large-scale structure as well as a broad variety of properties of galaxies of the different morphological types (Granato et al. 2000 and references therein). Serious shortcomings of this scenario have also become evident in recent years.

At the other extreme of the galaxy mass function with respect to so-called "small-scale crisis", another strong discrepancy with model predictions arises, that we might call "the massive galaxy crisis". Even the best semi-analytic models hinging upon the standard picture for structure formation in the framework of the hierarchical clustering

paradigm, are stubbornly unable to account for the (sub)-mm (SCUBA, see Fig. 1, and MAMBO) counts of galaxies, most of which are probably massive objects undergoing a very intense star-burst (with star formation rates $\sim 1000\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$) at $z > 2$. Recent optical data confirm that most massive ellipticals were already in place and (almost) passively evolving up to $z \simeq 1$–1.5. These data are more consistent with the traditional "monolithic" approach whereby giant ellipticals formed most of their stars in a single gigantic starburst at substantial redshifts, an underwent essentially passive evolution thereafter.

In the canonical hierarchical clustering paradigm the smallest objects collapse first and most star formation occurs, at relatively low rates, within relatively small proto-galaxies, that later merged to form larger galaxies. Thus the expected number of galaxies with very intense star formation is far less than detected in SCUBA and MAMBO surveys and the surface density of massive evolved ellipticals at $z \gtrsim 1$ is also smaller that observed. The "monolithic" approach, however, is inadequate to the extent that it cannot be fitted in a consistent scenario for structure formation from primordial density fluctuations.

2. Relationships between quasar and galaxy evolution

The above difficulties, affecting even the best current recipes, may indicate that new ingredients need to be taken into account. A key new ingredient may be the mutual feedback between formation and evolution of spheroidal galaxies and of active nuclei residing at their centers. In this framework, Granato et al. (2001) elaborated the following scheme.

Feed-back effects, from supernova explosions and from active nuclei delay the collapse of baryons in smaller clumps while large ellipticals form their stars as soon as their potential wells are in place; *the canonical hierarchical CDM scheme – small clumps collapse first – is therefore reversed for baryons*. Large spheroidal galaxies therefore undergo a phase of high (sub)-mm luminosity.

At the same time, the central black-hole (BH) grows by accretion and the quasar luminosity increases; when it reaches a high enough value, its action stops the star formation and eventually expels the residual gas. The same mechanism distributes in the inter-galactic medium a substantial fraction of metals. The duration of the star-burst, imposed by the onset of quasar activity, increases with decreasing mass from ~ 0.5 to $\sim 2\,\mathrm{Gyr}$.

This implies that the star-formation activity of the most massive galaxies quickly declines for $z \lesssim 3$, i.e. that the redshift distribution of SCUBA/MAMBO galaxies should peak at $z \gtrsim 3$, as quasars reach their

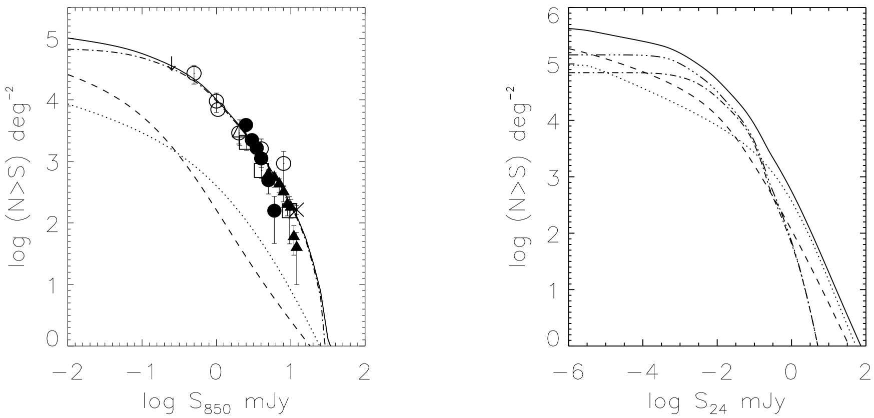

Figure 1. Left hand panel: integral source counts at 850 μm predicted by the model by Granato et al. 2001 compared with observations. The dotted, dashed, dot-dashed and solid lines show the contributions of starburst, spiral, forming elliptical galaxies, and total respectively. Right hand panel: integral source counts predicted by the same model. The dotted, dashed and dot-dashed lines show the contributions of starburst, spiral, and forming elliptical galaxies, respectively, while the three-dots/dashed line shows the total counts of ellipticals, including also those where the star-formation has ended.

maximum luminosity (at $z \simeq 2.5$). This explains why very luminous quasars are more easily detected at (sub)-mm wavelengths for $z \gtrsim 2.5$.

A "quasar phase" follows, lasting 10^7–10^8 yrs, and a long phase of passive evolution of galaxies ensues, with their colors becoming rapidly very red [Extremely Red Object (ERO) phase]. Intermediate- and low-mass spheroids have lower Star Formation Rates (SFRs) and less extreme optical depths. They show up as Lyman-Break Galaxies (LBGs).

Therefore, in this scenario, large ellipticals evolve essentially as in the "monolithic" scenario, yet in the framework of the standard hierarchical clustering picture. Many aspects and implications of this compound scheme have been addressed by our group in a series of papers (Granato et al. 2001, Magliocchetti et al. 2001, Perrotta et al. 2001, Romano et al. 2001). Here we only summarize how the scenario compare with sub-mm counts.

2.1. Counts at (sub)-mm wavelengths

The (sub)-mm counts are expected to be very steep because of the combined effect of the strong cosmological evolution of dust emission in spheroidal galaxies and of the strongly negative K-correction (the dust

emission spectrum steeply rises with increasing frequency). The model by Granato et al. (2001) has extreme properties in this respect: above several mJy its $850\,\mu$m counts reflect the high-mass exponential decline of the mass function of dark halos. In this model, SCUBA/MAMBO galaxies correspond to the phase when massive spheroids formed most of their stars at $z \gtrsim 2.5$; such objects essentially disappear at lower redshifts. On the contrary, the counts predicted by alternative models (which are essentially phenomenological) while steep, still have a power law shape, and the redshift distribution has an extensive low-z tail. As illustrated by Fig. 1, the recent relatively large area surveys are indeed suggestive of an exponential decline of the $850\,\mu$m counts above several mJy. Further evidence in this direction comes from MAMBO surveys at 1.2 mm.

2.2. Predictions for SIRTF surveys

SIRTF surveys have the potential of providing further tests of the model. In particular the $24\,\mu$m survey to be carried out as a part of the GOODS (http://www.stsci.edu/science/goods) Legacy Science project should reach a flux limit of $100\,\mu$Jy. According to the model, about 50% of detected galaxies should be spheroidal galaxies forming their stars at $z \gtrsim 2$. About 400–600 such objects are expected over an area of 0.1 square degree (see Fig. 2). Their redshift distribution is predicted to peak at z slightly above 2, with a significant tail extending up to $z \simeq 3$.

Acknowledgements

We benefited from many helpful exchanges with C. Baccigalupi, F. Matteucci, F. Perrotta, D. Romano. Work supported in part by ASI and MIUR. G.L.G. thanks SADG for partial financial support.

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